Interpretation of Crustal Deformation Measurements in Southern California

Program Elements/Objectives: II-3 and II-7

December 1, 1992 — August 30, 1995
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Submission date: November 30, 1995

---- FINAL TECHNICAL REPORT ----

1434-93-G2307

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--- NONTECHNICAL SUMMARY REPORT ---
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Our research under this grant has focused on understanding the errors in, and improving the accuracy of, crustal deformation measurements, since these measurements give the only direct data about the buildup of strain between earthquakes. This has involved comparing results from both complementary and competitive measurement systems. We have analyzed data from a 14-km line measured with the Global Positioning System (GPS) to understand the accuracy of this new technique; we have also been designing, building, and testing improved methods of constructing geodetic monuments. In addition, we have investigated sources for surprising crustal motions seen after the 1992 Landers earthquake.

Abstract

This grant has supported analysis and interpretation of data on crustal deformation in southern California, especially data collected at Piñon Flat Observatory (PFO), with focus on the following:

- **Sources of postseismic crustal motion**: We have worked on the analyses of the data collected at PFO before and after the Landers earthquake, which show deformations unprecedented in the history of the observatory. We have concluded that of the possible sources for the postseismic signal, the most likely appears to be aseismic fault slippage occurring in different proportions (and perhaps at different locations) than the seismic part of the rupture did—a result of importance to understanding the stress changes imposed by this earthquake.
- **Better Modeling of Fault Slippage**: We have processed GPS and two-color EDM data around PFO to get an estimate of the far-field coseismic strains from this earthquake. We have begun working on ways to apply a dislocation model for a *layered medium* to these data, and to the extensive GPS estimates of coseismic displacement throughout southern California, so as to develop an improved model for the earth, the source, and for the distant deformations. Initial estimates show the effects of layering to be important at large distances, something which has not been used in earlier calculations.
- **Detection of anomalous deformations**: Guided by our studies of the Landers postseismic signal, we have investigated how various types of deformation data can be applied to determine, or at least bound, possible aseismic fault motions: the goal being to produce a system for deducing, from the data available, whether some kind of anomalous motion has occurred. We would hope to be able to apply this to the PFO data—an potentially valuable task given the higher possibility of unusual changes in the wake of the Landers event. A natural and useful byproduct of this is a method for evaluating the ability of a specified network of sensors (installed or planned) to detect unusual deformation.
- **Fault-scale GPS**: We have continued our studies on the accuracy of GPS measurements at short (<20 km) distances, by analyzing data from a 14-km continuously-monitored line set up in mid-1990. With this kind of data we are not limited to estimating just the short-term or long-term scatter, but can find the true error spectrum, and thus have been able to provide guidelines for fault-scale GPS studies.
- **Monumentation**: A significant source of error in geodetic studies at fault-scale distances is instability of the monuments. We have continued our investigations of monument stability, using the large array of monuments of different types already installed at PFO and at the new laser strainmeter at Durmid Hill; and also continued to develop new types of monument design. Both this project and the previous one are of course of great importance for the dense GPS arrays now planned for the Los Angeles area, and being considered elsewhere.
- **Cooperative Investigations**: We have continued our cooperative studies with investigators working at PFO under the sponsorship of the U.S. Geological Survey NEHRP, on developing, comparing, and evaluating improved methods for measuring ground deformations for periods from seconds to years. This includes comparisons of geodetic techniques (such as 2-color EDM and GPS), as well as studies of strainmeters and tiltmeters.

Our overall aim has been a better understanding of the meaning, and realm of usefulness, of all forms of crustal deformation measurement.

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Interpretation of Crustal Deformation Measurements in Southern California

1434-93-G2307

Duncan Carr Agnew, Frank K. Wyatt, and Hadley Johnson

1. Introduction

Under support of this grant we have pursued research on crustal deformation, applied specifically to earthquake studies in southern California. A large part, though not all, of this research has made use of data from Piñon Flat Observatory (PFO), at which a wide range of measurements allow information to be gained that otherwise could not be. **Figure 1-1** shows the location of PFO (and of our satellite observatory site, DHL, at the southern end of the San Andreas), relative to faults, historic faulting, and seismicity—along with conservative estimates for slip deficit (dashed arrows) for the two best understood fault systems. While the work we have done has the most direct application to southern California, most of our results should be of use in many different regions. Since crustal motions give the only direct view of interseismic processes, understanding them is essential to attaining the goals of the NEHRP; and observations of these motions, by a variety of techniques, has been, and continues to be, an important part of both the internal and external research programs.

This research in crustal deformation originally focussed on collaboration with other investigators supported by the NEHRP to make measurements at PFO; we collaborated on instrument operation, joint data-processing, intercomparison of instruments, and understanding what the data meant. From these efforts, everyone involved has gotten a better understanding of crustal deformations and of the merits and demerits of the methods used for measuring them; these lessons having been learned (we hope), we have been able to broaden our research focus.

This report covers a number of research projects, and, as has to be true when fielding a such range of activities (and with the occurrence of such unanticipated events as the Landers and Northridge earthquakes), they are at various stages of completion. Not all are completely done, though several are, and we would like to think our publications speak to the progress we have made during this grant period.

2. Cooperative Studies

2.1. Instrument Investigations.

As noted above, much of the initial rationale for cooperative studies at PFO was to compare different classes (and modes of installation) of different instruments, mostly for the measurement of crustal deformation. This resulted in some fairly clear indications of what worked and what didn't; unfortunately, given the recent funding climate, the main practical result was to supply reasons for eliminating those measurements that didn't work, rather than installing many more of those that did.


Southern California Faults and Earthquakes
Seismicity
1976 - 1992
Dashed Arrows:
est. slip deficit
1857
3.0m
San Bernardino
1992c
0.6m
1992b
3.5m
1992a
0.4m
San Andreas
Palm Springs
Piñon Flat
Observatory
PFO
1890/99/1918
1.3m
1.2m
6m
Durmid
Hill
DHL
Salton
Sea
San Jacinto
1954
0.35m
1942/68
0.7m
1987a
0.3m
1987b
1.1m
1940/79
1.2m
El Centro
Elsinore
San Diego
Pacific
Ocean
Baja California
34°
33°
North Latitude
118°
117°
116°
115°
East Longitude

Figure 1-1

The explicit comparison phase of the program is now largely completed, though it lives on in three respects: **(1)** For those instruments with very low marginal cost of operation, it makes sense to keep them running (until they fail), since redundancy of measurements very often proves to be useful in unexpected ways.[1] Some results from this phase of the project are still in the course of publication; as one publication to which earlier versions of this grant in part contributed, we would mention the results on borehole tilt measurements by Kohl and Levine (1993), who show that borehole tiltmeter measurements (of the tides and hence of other tilts) can be seriously distorted by local inhomogeneities, even to the level of depending on the coupling of the tiltmeter capsule to the borehole casing.

(2) Not covered by this grant, but mentioned for completeness, are comparisons of instruments other than those for measuring crustal deformation; this goes on at PFO because of the facilities available there. One recent example has been the installation of several types of borehole seismometers (funded by RIDGE and by IRIS) to test for future deep-ocean deployments, and compare the noise levels of different modes in installation of sensors (vault/posthole/borehole). The marginal costs to the observatory of doing this, as well as of operating the redundant instruments mentioned above, are covered by what funds are available for operation of PFO as a facility.

(3) This grant also covered the comparison of geodetic systems. One result of the last decades's work, by us and by others, has been a general skepticism about possible short-term variations in crustal deformation (months and less): the general rule for these seems to be that (outside of volcanic areas) the more carefully you look, the less you see.[2] But there remains a part of the crustal deformation spectrum that has not yet been well explored: periods from months to a few years. **Figure 2-1**, which shows the best available strain record from PFO, makes the problem clear. Only the best-quality strainmeter (as here, with full anchoring) has low enough drift to be stable at these periods; conventional geodetic data have too little resolution, in either time or strain, to be able to see fluctuations of the size that the strainmeter suggests might be taking place (as, for example the clear increase following the Landers earthquake, and the less certain decrease starting in early 1993). (Larger fluctuations, over longer times, are ruled out by the geodetic data themselves: Savage *et al.* (1986), Johnson *et al.* (1994a)). With the rapid development of continuous GPS, the possibility exists for additional, and improved, monitoring of this part of the deformation spectrum; but how good a possibility this is depends on how good the geodetic data turn out to be. Section 3 is devoted to our studies of this question; here we wish only to point out the wide range of geodetic monitoring that has gone on (and in many cases continues to go on) around PFO.

Figure 2-2 shows the area around the observatory, emphasizing the geodetic networks. The longest-running one of these was the single-color Geodolite network, part of the larger Anza net, surveyed from 1973 through 1991 by the Crustal Strain group of the USGS. This has now been replaced by GPS surveys done by us. In 1986, the USGS also set up a two-color EDM network across Pinyon Flat; it is surveyed roughly quarterly. This array spans 4-km distances, and so is intermediate in length between the 20-km lengths of the Geodolite network, and the 500 to 700-m-long lines of the observatory instruments, as is a GPS "footprint array" for the NCMN monument at PFO, which was at one time used by the NASA mobile VLBI systems. The role of VLBI in

[1] As a quite recent example, it was data from shallow-borehole Kinemetrics tiltmeters, which we had left running but not maintained since 1985, which helped to eliminate local groundwater effects as a possible source for the 1992 Landers postseismic strain signal.

[2] Though there have been some positive results: the preseismic signal of Gladwin *et al* (1991), the Landers postseismic signal (Wyatt *et al.* 1994), and the swarm-related signal of Johnston *et al* (1993).

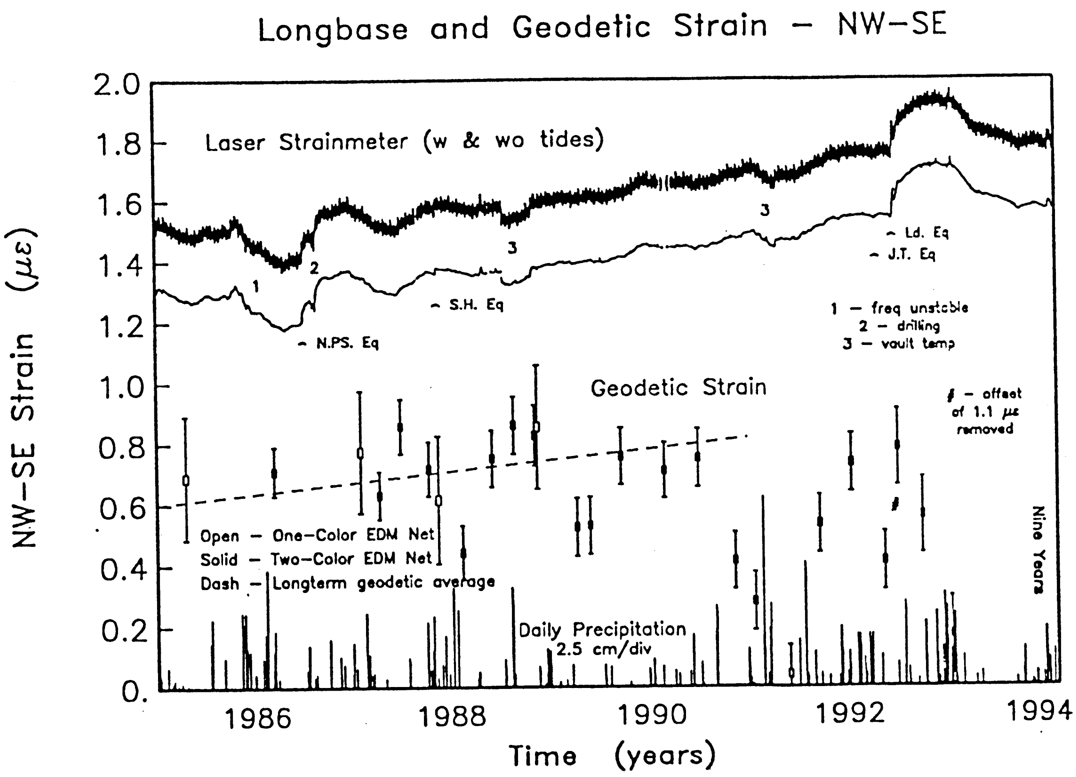


Figure 2-1

tying PFO to a global reference frame has now been assumed by the continuous GPS system (the PGGA) run by UCSD. The University of California, Santa Barbara conducts occasional geodetic levelings around a small kilometer-scale loop at PFO; from 1986 through 1988 the USGS and NGS levelled a 14-km-long line across Pinyon Flat. Absolute gravity measurements have been made by groups from UCSD and the NGS.

2.2. Strain Seismology

The laser strainmeters at PFO can easily record strains from seismic waves: their response is flat from DC to an upper limit set by spatial aliasing, as the wavelength of the seismic waves becomes comparable to the 732-m length of the instruments. While the dynamic range, in the absence of strong shaking, is in principle infinite, it is in practice limited by the reset level of the fringe-counter circuits (presently 2^{16} quarter-fringes, or 7 $\mu\varepsilon$) and datalogger (presently 0.44 $\mu\varepsilon$). We have, since the inception of the project, recorded the strain output at at least 1-s sampling, for possible use in seismic data analyses; but it is fair to state that the data have not been in great demand, not because of instrument deficiencies, but because strain recordings do not, for most analyses, add much to the information available from inertial sensors, and usually have a poorer signal-to-noise ratio.[3]

[3] That this is a general conclusion, not peculiar to the PFO data, is shown by the rather lackluster results of years of work on "strain-inertial" seismographs, funded by the ARPA seismic discrimination program; see Farrell (1985).

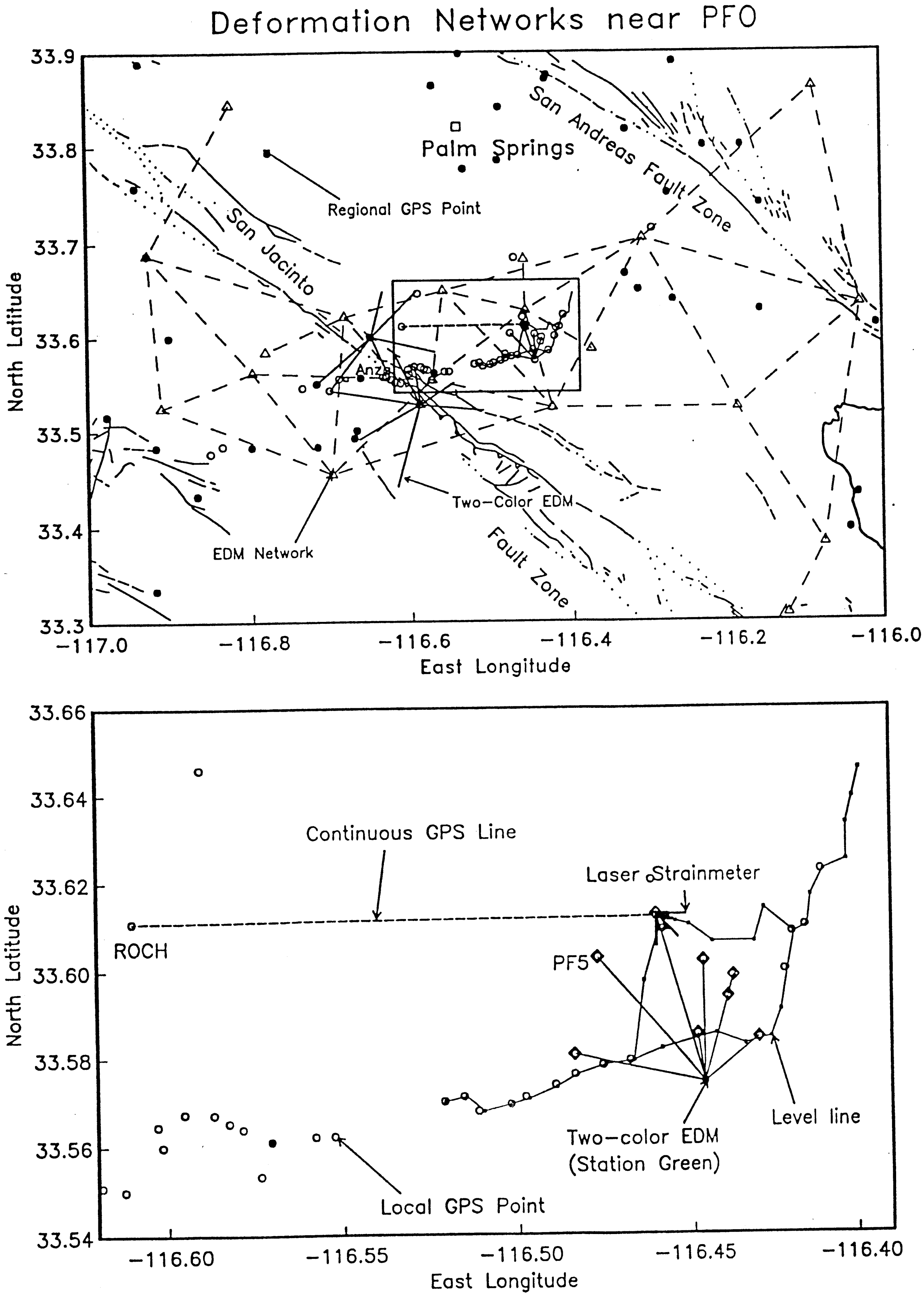

Deformation Networks near PFO
Palm Springs
San Andreas Fault Zone
San Jacinto
Fault Zone
Regional GPS Point
Anza
Two-Color EDM
EDM Network
North Latitude
East Longitude
33.9
33.8
33.7
33.6
33.5
33.4
33.3
-117.0
-116.8
-116.6
-116.4
-116.2
-116.0
Continuous GPS Line
Laser Strainmeter
ROCH
PF5
Two-color EDM
(Station Green)
Level line
Local GPS Point
33.66
33.64
33.62
33.60
33.58
33.56
33.54
-116.60
-116.55
-116.50
-116.45
-116.40

Figure 2-2

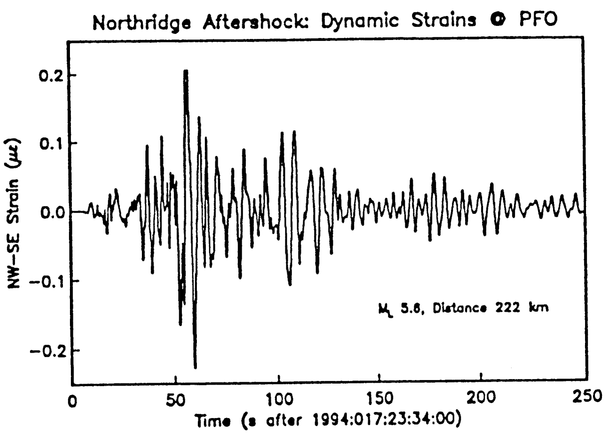


Figure 2-3

The widespread triggering of seismicity following the Landers earthquake (Hill *et al.* 1993) has created a new reason for wanting to look at seismic waves in terms of strain. Since the static stress changes fall off much more rapidly with distance than the ones from seismic waves, and since the pattern of triggered seismicity seems to reflect the pattern of peak velocities (roughly proportional to strain), it seems likely that understanding the strain changes (and hence stress changes) changes caused by these waves will help to understand why triggering did and didn't occur.

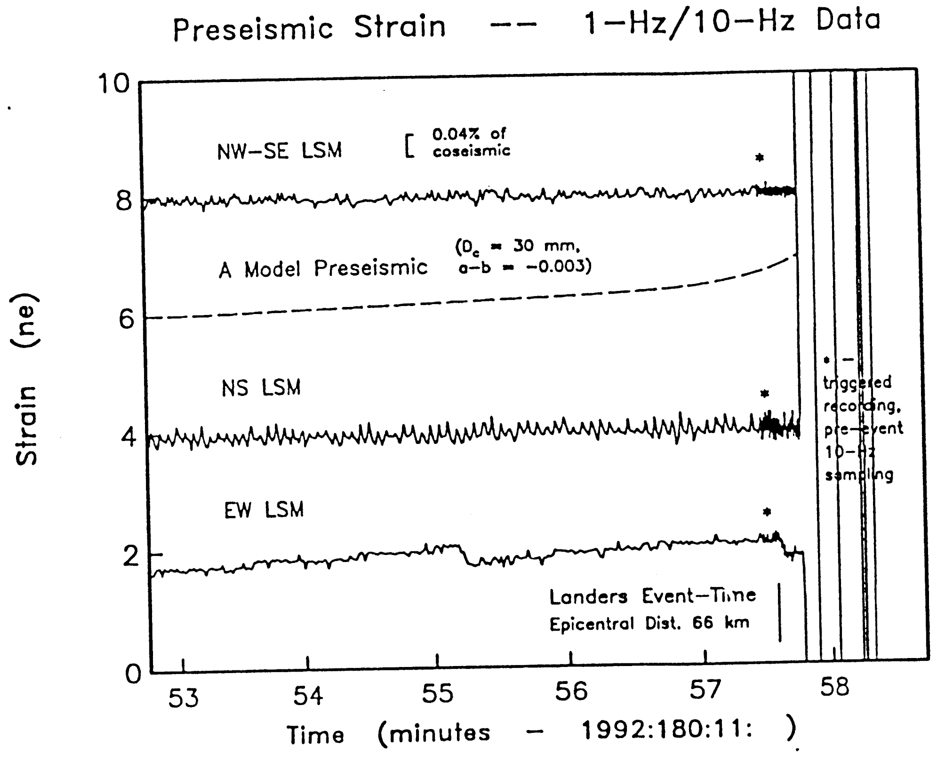
This question is being investigated by Dr. Joan Gomberg (USGS–Denver), under an internal USGS grant. The first step is to be able to compute what the strains were, requiring a synthetic-seismogram program that computes strains rather than displacements; Dr. Gomberg has developed this, and is testing it using data from the PFO laser strainmeters, recorded for various events at regional distances. (Some other data is available from the dilatometers operated by the USGS in California, but of course these do not allow the recording of shear strain). **Figure 2-3** shows one example, namely a component of strain at PFO for a large aftershock of the Northridge earthquake.

2.3. The Landers Earthquake: Initiation and Afterslip

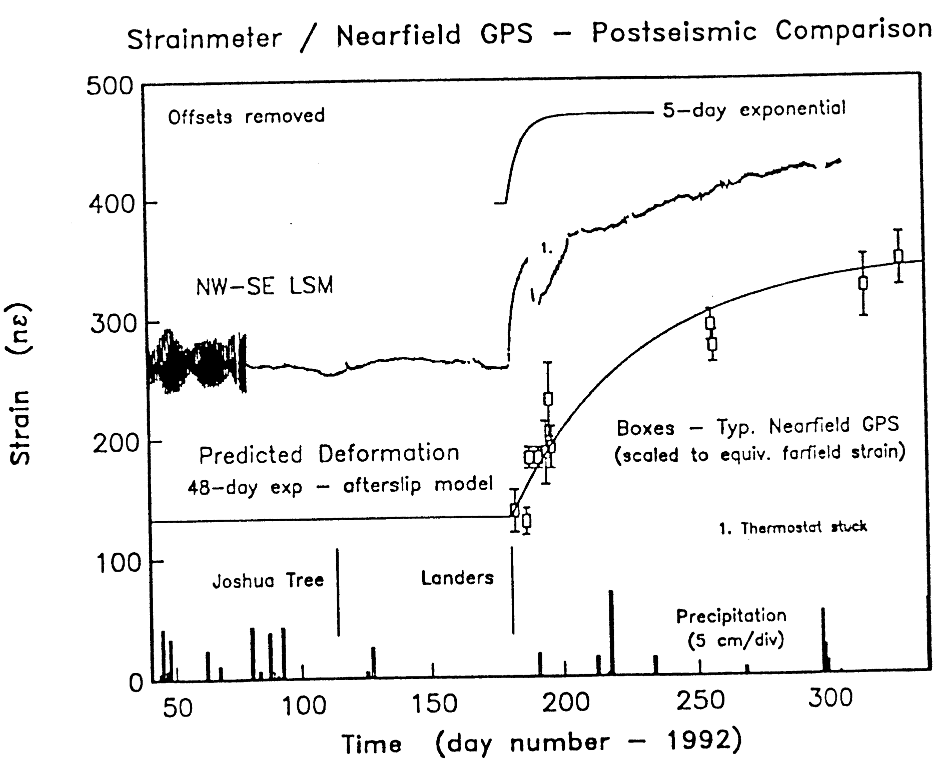
The data from the Landers earthquake sequence was unique in our experience at PFO: both in the proximity to a large earthquake, and in the substantial postseismic signal seen in the deformation sensors. We have observed postseismic signals earlier (Wyatt 1988; Agnew and Wyatt 1989), but never before have they been anywhere near as large or as long-lasting. Wyatt *et al.* (1994) describes the PFO results.

Figure 2-4 shows a selection of the data from PFO for this sequence. For the preseismic strain (top plot) the result was a familiar one: nothing convincingly unusual is identified—this time with an even smaller limit ($\sim10^{-4}$ of the coseismic strain) than we have been able to set before. The lower plot shows the postseismic, "exponential like" strain seen in all the instruments. From this, and the other PFO data, we conclude that there was a strain and tilt change following the Landers earthquake that was both large and rapid compared to the deformations normally observed; the only deformation larger and more rapid being the coseismic deformation itself. We can use the variety of instruments at PFO to make a strong case that this deformation extended uniformly over at least the kilometer scale of the observatory, and probably well beyond. Possible mechanisms for this rapid deformation include, in principle, various kinds of coupling to the water table, though in practice none of these seem capable of providing large, rapid, uniform strains.

Surprisingly, the most straightforward cause for the postseismic signal, that of accelerated postseismic slip on or at the edges of the ruptured fault planes, and in proportion to the coseismic slip, is ruled out by the observed patterns of strains and tilts at PFO, although the Big Bear rupture is suggested as a possible source. This is different from our past experience: all previous measurements at PFO have shown that the best sensors indicate either no detectable postseismic signal, or



Preseismic Strain -- 1-Hz/10-Hz Data
NW-SE LSM
0.04% of coseismic
A Model Preseismic
(D_c = 30 mm, a-b = -0.003)
NS LSM
EW LSM
* - triggered recording, pre-event 10-Hz sampling
Landers Event-Time
Epicentral Dist. 66 km
Strain (ne)
Time (minutes - 1992:180:11:)



Strainmeter / Nearfield GPS - Postseismic Comparison
Offsets removed
5-day exponential
NW-SE LSM
Predicted Deformation
48-day exp - afterslip model
Boxes - Typ. Nearfield GPS
(scaled to equiv. farfield strain)
1. Thermostat stuck
Joshua Tree
Landers
Precipitation
(5 cm/div)
Strain (nε)
Time (day number - 1992)

Figure 2-4

one fully in accord with the coseismic deformation and 5% to 10% of it in size. It is important to realize that if the primary cause of the smoothly varying signals at PFO is not fault slip, these data then imply that there was very little aseismic afterslip (there being little other character to the observations), which has implications for fault physics.

Perhaps the most important candidate mechanism for the observed signals is transient creep of the upper part of the crust in response to the large stress change imposed by the elastic rebound that drives the earthquake: stress-induced changes in microcracks in materials not under high confining pressures. Further modeling will be needed to determine how large an effect such as this might reasonably be; if it should turn out to be large in the area of significant stress change, the unequivocal observation of postseismic fault motion might remain forever impossible, being obscured by crustal response in the only locations where it is large enough to rise above instrumental noise.

Dr. R. Abercrombie (just moved to New Zealand) has spent some time examining the foreshock sequence to the Landers mainshock (Abercrombie and Mori 1994). Recently that effort has extended to investigations into whether the foreshocks follow the pattern described by Ohnaka (1993), in which an expanding zone of foreshocks corresponds to an expanding nucleation zone for the mainshock. Such gradual ''stress corrosion'' would imply a slow slip prior to rupture, creating a far-field static strain. We have worked with Dr. Abercrombie in determining what limits the PFO data (strain, tilt, and GPS) place on such gradual slip, to see what mechanisms are appropriate for explaining both the seismicity and the absence of strain. The results of this cooperative work are currently in press (Abercrombie *et al.*, 1995).

Other evidence for postseismic deformation in the Landers sequence comes from the near-field GPS data collected by the UCLA GPS group of the Southern California Earthquake Center (SCEC) after the earthquake, and analyzed and described by Shen *et al.* (1994). Many of these stations showed postseismic displacements, though since the largest displacement was a few cm, the signal-to-noise was not high. These data could be fit with an exponential with a time constant between 15 and 150 days; this is probably consistent with the PFO data given the later start of the GPS measurements and their much lower signal-to-noise ratio. The spatial pattern of deformation implied slip both on the Landers rupture and on other fault segments as well. These results have recently been re-interpreted by Dr. R. Stein of the USGS as showing postseismic slip on the San Andreas in the area where it was most severely stressed by the Landers earthquake. Bulk inelastic behavior has been suggested by Wyatt *et al.* (1994) and by Ivins (1995) even for the short time constants of motion seen after the Landers earthquake, though the physics behind such behavior remains somewhere between unclear and speculative. We hope to work with the UCLA group (possibly with SCEC support) on a joint combination and inversion of these data. We would use the PFO data to provide a time history, assumed common to all stations; it will then be possible to use the GLOBK GPS adjustment program to determine the spatial pattern more completely and rigorously. We have considerable experience in inverting data for fault-slip models (see, for example, Johnson *et al* (1994b)), and would apply this to get possible models of the afterslip. Naturally, we also hope to test various models involving crustal relaxation, to see if the data can discriminate between these.

3. Geodetic Investigations

In the months immediately after the Northridge earthquake, the crustal deformation community in southern California was stimulated by the possibility that the existing network of permanent GPS stations (the PGGA, operated by our Scripps colleague Dr. Yehuda Bock) might be greatly expanded to a much denser array: going from 15 stations at ~100 km spacing, to 250 at ~10 km. It now seems certain that, thanks to funding from NASA, the USGS, and SCEC, a step at such a network will be made in the coming years. This is to be a joint UCSD/USGS/JPL/SCEC project (with our participation, primarily in advising on monumentation) funded by NSF and SCEC.

We have felt strongly that there is a need for additional research as such GPS densification gets underway. At a scale of 10 km, a continuous GPS system begins to look a lot like a long-base strainmeter: indeed, the ratio of this length to the strainmeter length is only a factor of 14. (For comparison, the ratio of scale between borehole strain and longbase strain is 3000–4000). We thus have considerable experience in the errors and problems associated with measurements on this scale, and have sought to apply it to the design of such systems. In doing this, we have drawn on data that we have been collecting with exactly such measurements in mind: continuous GPS over a 14-km baseline, and various estimates of monument stability.

3.1. Fault-scale Continuous GPS

Most studies of GPS errors have concentrated on distances of tens to thousands of kilometers. But for studies of fault behavior, especially in transcurrent environments, this scale is much too large: deformations over lengths of 1 to 50 km are what describe the pattern of strain accumulation around a fault. This realization is part of what is driving the current push to densify GPS stations to these scales. It then becomes important to understand the error spectrum, and error sources, of GPS over tens of km and less. Knowing these errors is important in planning how best to combine, not just GPS measurements and other data, but also different modes of observation with GPS. For example, a lower-cost alternative to continuous GPS would be occasional unattended occupation of the same locations. This could not of course detect fluctuations, but could still determine (in a longer time) the secular strain rate. To decide how much longer, and thus how cost-effective this mode would be, we need to know the errors of the data. Any short-term correlation would imply that measurements could be spaced a few days apart with little loss; any long-term correlation (redness of the spectrum) would imply that having many measurements would not in fact gain as much as might be thought compared to fewer over a longer time; and any non-normality (especially large outliers) would argue for more frequent observations, to make the results more robust.

In order to have data with which to address this question, we have been running continuous GPS over a 14-km baseline since the summer of 1991, with the support of the predecessors of this grant.[4] This effort is similar to one being carried out by the USGS Crustal Strain Group in Menlo Park, under the direction of Dr. Nancy King (King *et al.* 1992). **Figure 2-2** shows the location of this GPS line, extending west from PFO to a site at Pine Meadow (ROCH); while this intentionally does not cross the San Jacinto fault, it is within the region of strain accumulation.[5] At both ends of the line we have operated Trimble 4000 SST receivers, each connected to a PC so as to operate as a continuous tracker; a modem is used to download the data over a dialup phone line. At ROCH the antenna is mounted on a post set into a massive granite outcrop; at PFO (site PIN2), the antenna is mounted on one of our deeply-anchored monuments (Section 3.2). At PFO there is also data available from P-code receivers operated at the main PGGA mark, PIN1. We first planned to measure the PIN2-ROCH baseline for a year and a half; because of the occurrence of the Landers earthquake, we extended this to the present, in order to look for possible response to the stress change imposed on the San Jacinto fault, and any other reactions to the Landers sequence.

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4 This experiment has been possible because of the assistance of Dr. David Jackson (UCLA) in providing equipment, and of Dr. Yehuda Bock (IGPP) in providing advice and online data storage.

5 Assuming 1 cm/yr motion at depth on the San Jacinto fault, with no motion above 5–10 km, we expect ROCH to be moving 1.3 mm/yr westerly away from PFO, and 0.9 mm/yr to the north.

Figure 3-1 shows both the data available to us (lower half), and what has been processed. Unfortunately, the processing was the project of a graduate student who, after an initial burst of productivity (resulting in the presentation by Happer *et al.* 1991) decided that he was unsure of whether he wanted to continue or not: a lengthy phase that ended with his departure, and during which it was impossible to pass the project to anyone else. For this reason, and some technical difficulties in getting programs working properly, we have not made as much headway on this project as we had hoped. **Figure 3-1** does contain enough data from before and after the Landers earthquake to confirm the results of dislocation modeling (shown, along with the values already mentioned for the interseismic motions, as the "Theoretical" lines). A more tantalizing result is the apparent change in rate between the period before the Landers earthquake and that after it; though since the rate before was much higher than expected, and that after (though closer to the model) is based on few points, we are suspicious of the reality of this signal. Processing the whole data set will clear this up. If the change in shear stress on the San Jacinto fault (Harris and Simpson 1992) causes a change in the rate of slip, these data are our best chance to see it.

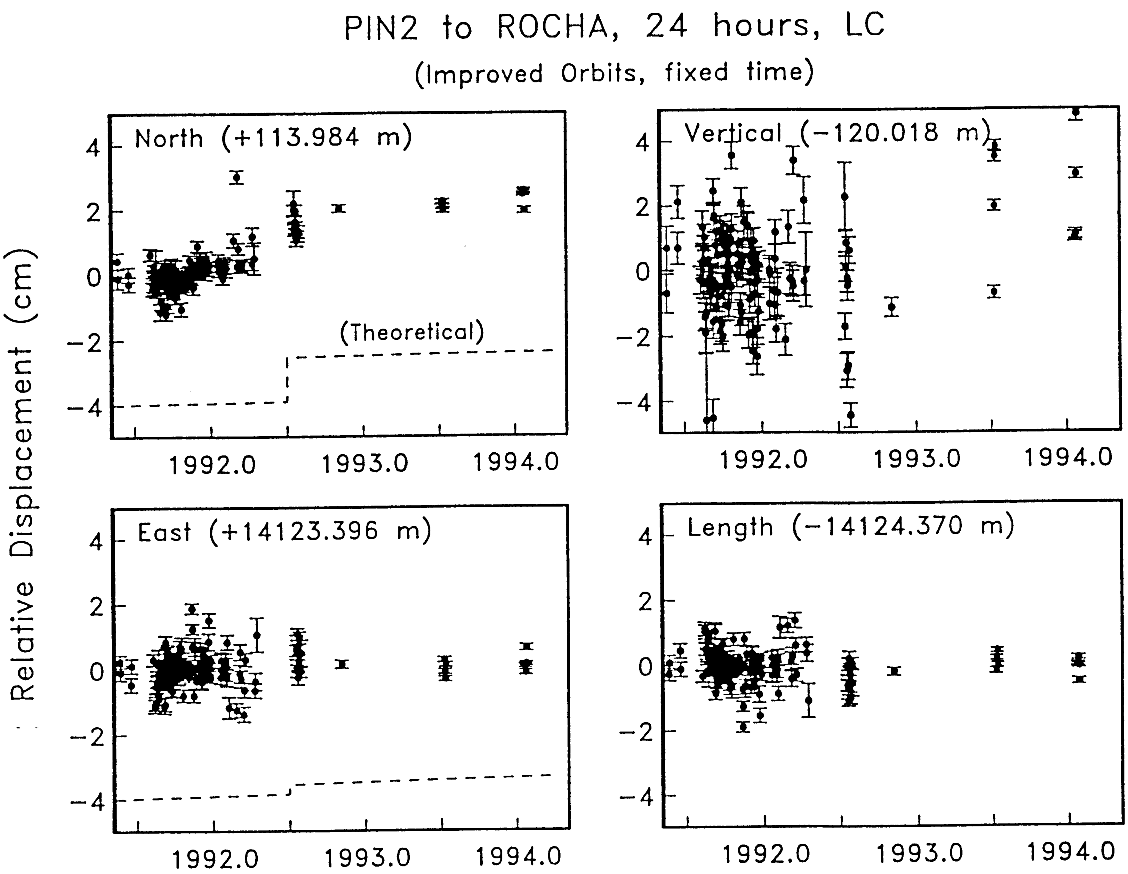
One result from our processing of the data is that over the very short (50 m) line from PIN1 to PIN2 the error is less than 0.5 mm for *L1*/*L2*, and about 3 times this for *LC*: presumably the noise floor for this class of receivers. Over 14 km the 1991 data show a scatter in both the horizontal and vertical components that is about four times as large. We attribute this increased scatter to the effect of different tropospheric delays at PIN2 and ROCH. This scatter is not much greater than what was then seen on the 100+ km lines of the PGGA, implying that the troposphere is just as uncorrelated over a 14-km distance as it is over longer lines.[6] The fluctuations also appear to be correlated, perhaps over times longer than a week, though more data will be needed to be sure of this.

3.2. Monument Stability

One of our long-running concerns has been the stability of geodetic monuments: a major factor in the quality of data from strainmeters and tiltmeters, and with the move toward closely-spaced GPS, probably a major influence on this dataset as well. **Figure 3-2** shows what may be taken as a cautionary lesson in this regard, coming from the only system that is comparable to (probably better than) continuous GPS over short distances: the permanent two-color EDM at Parkfield. (These data are courtesy of Dr. John Langbein of the USGS, with whom, as we explain below, we have been collaborating with the result of a paper now in press: Langbein *et al.*, 1996). The three marks for which we show data are in about the same azimuth; the low variability of the detrended distance to LANG shows the stability of this mark, and of the instrument. The other two marks, MIDD and POMO, show definite seasonal, but opposite, fluctuations of order 10 mm—in the case of POMO, not even stationary with time. (The shaded lines show the approximate onset time of the wet season for the last few years.) In a pattern familiar to us from PFO, these marks all move considerably at the onset of each rainy season, reversing as the ground dries.

Clearly, such cyclic behavior is a problem for any measurement, and disastrous if the aim is to look for fluctuations. Indeed, even for the determination of secular-strain parameters monument motion can be the biggest source of error. This is the result of a simulation study by Johnson

6 Perhaps because of the increased number of satellites, more recent PGGA data shows a decreased scatter.


PIN2 to ROCHA, 24 hours, LC
(Improved Orbits, fixed time)
Relative Displacement (cm)
North (+113.984 m)
(Theoretical)
Vertical (−120.018 m)
East (+14123.396 m)
Length (−14124.370 m)
4
2
0
−2
−4
1992.0
1993.0
1994.0

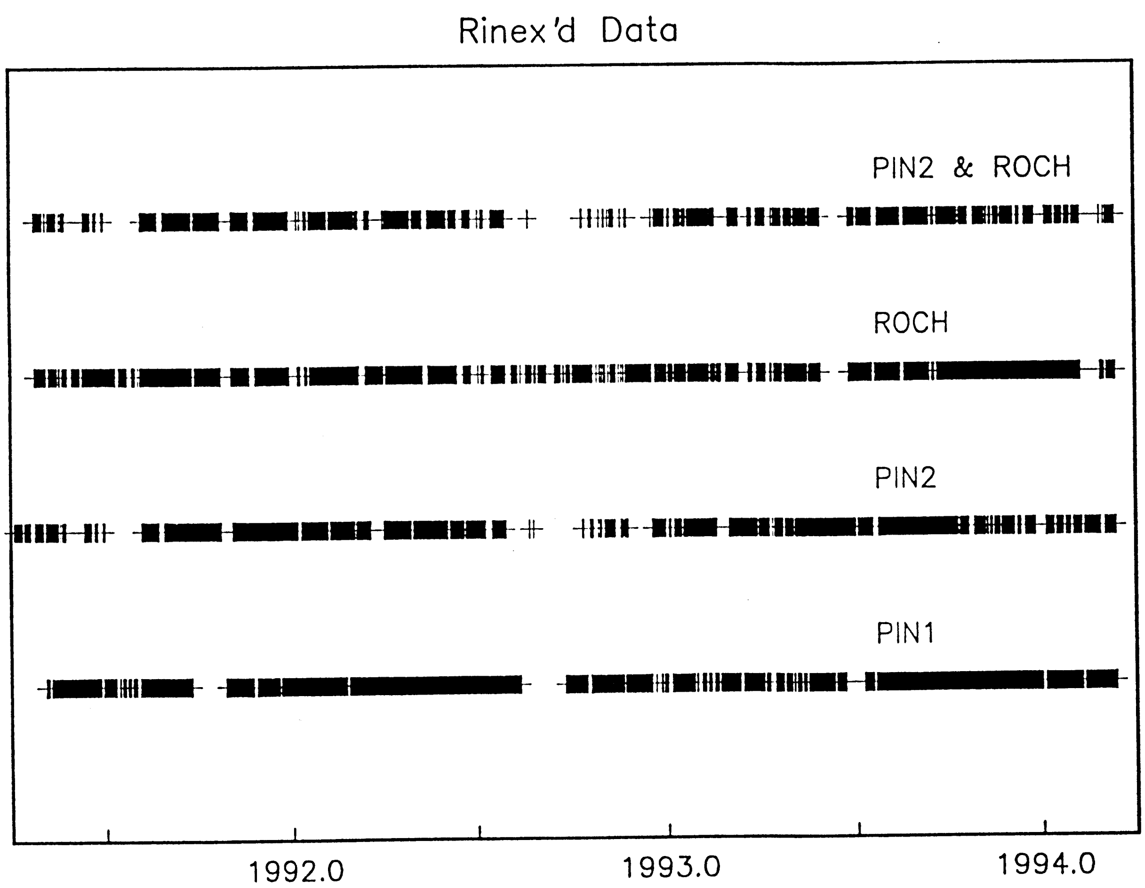

Rinex'd Data
PIN2 & ROCH
ROCH
PIN2
PIN1
1992.0
1993.0
1994.0

Figure 3-1

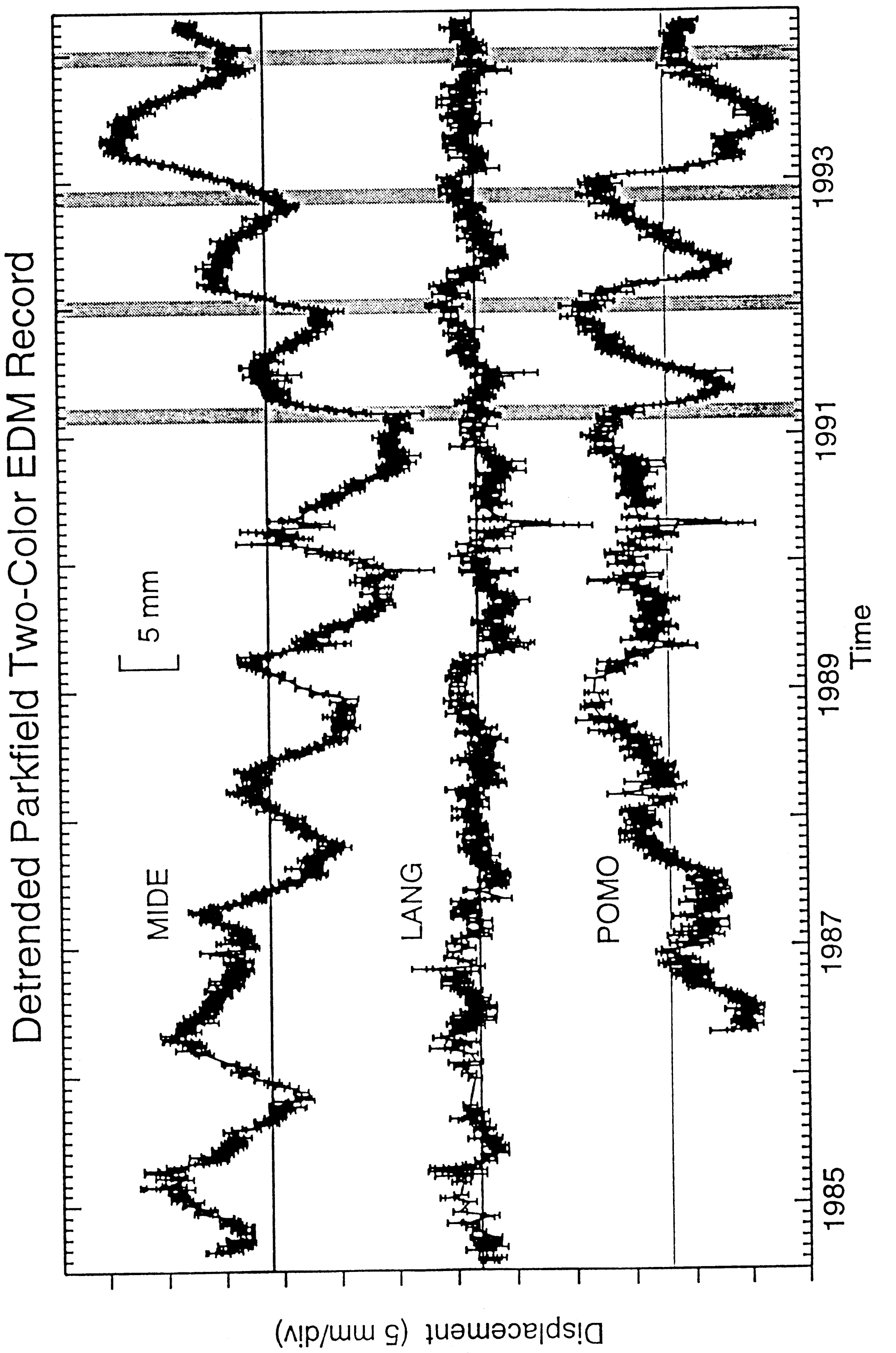

Detrended Parkfield Two-Color EDM Record
MIDE
LANG
POMO
5 mm
1985
1987
1989
1991
1993
Time
Displacement (5 mm/div)

Figure 3-2

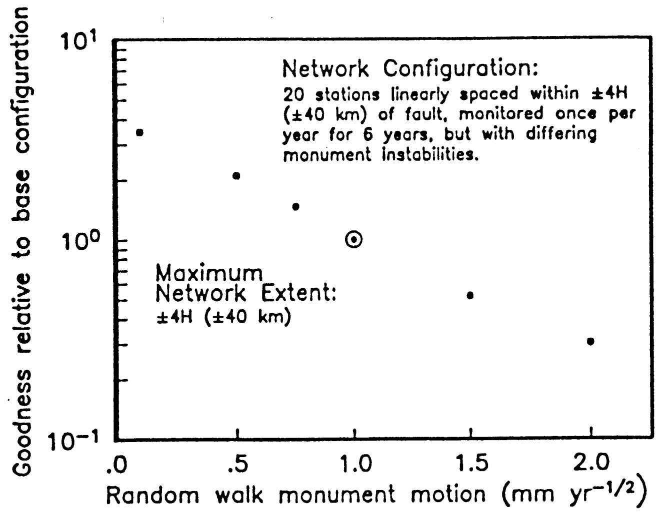


Figure 3-3

and Wyatt (1994), one of whose results we give in **Figure 3-3**. This shows the relative "goodness" (ability to determine fault parameters) of a geodetic survey as a function of monument instability: as the instability increases, the results become much poorer. Indeed, this parameter had a stronger effect on the quality of the result than any other; the number of years occupied by the survey was the next most important parameter, with number of occupations much less important. With poor monuments you are especially likely to get very poor returns on your efforts.

What can be done? The marks at Parkfield are well constructed piers, sunk ~ 2 m deep into the soil and isolated from the top 0.75 m of the ground; this is the conventional approach to building survey monuments, and is clearly insufficient. An extension of this technique, tested in detail by Bilham (1993) (and independently proposed by Karcz *et al* (1992)) is to use a pipe extending to depth, and monitor the motion of the top relative to depth using an inclinometer traversing the pipe. Bilham's results demonstrate that this approach can give precision of 1 mm or better; unfortunately it requires a manual measurement, and is thus not very compatible with getting continuous data. We have constructed several marks in which the position of the mark relative to points at depth is continuously monitored using optical interferometers. This works well, but even the low-maintenance versions of these (using optical fibers) are not engineered to the level where they are suitable for general use (though some amount of development funds—perhaps $200,000—would go a long way toward rectifying this).

The compromise approach we have followed, where the highest stability (< 1 mm/yr) is not needed, is to construct deeply-anchored monuments in which the anchoring is provided by a trusswork of pipes cemented to depth in drilled holes; **Figure 3-4** gives an example, shown to scale with the conventional monuments in use at Parkfield. Table 3-1 gives a list of those deep monuments we have built so far. While the initial impetus was to provide high-quality monuments for the stations of the PGGA/SCIGN, we have also built marks at PFO and at Parkfield to be used in the two-color net there. We feel that the construction of these marks has educated us about this technique, to the point that we can generate clear specifications for future constructions of this type, with good assurance that the marks built will be long-lived. It has also, we think, been a stimulus to the rest of the community. As evidence of this we can point to the angled-rod installation developed by Dr. Ken Hudnut for use at the PGGA site in Blythe; this, by using driven rods rather than drilled ones, offers a less costly method of installation that should work about as well in deep alluvium.

One of the difficulties of this research has been the problem of how to test the results: this requires a known stable point and highly accurate surveys between it and the other marks. (For the initial anchoring of the end-monuments of the laser strainmeters, the proof was in the improved quality of the results.) We have followed two approaches to this. One has been the establishment of several "monument clusters" at Pinyon Flat, summarized in Table 3-2. The first of these was established in 1986 when the NGS installed some of their new rod-marks in an area near one end

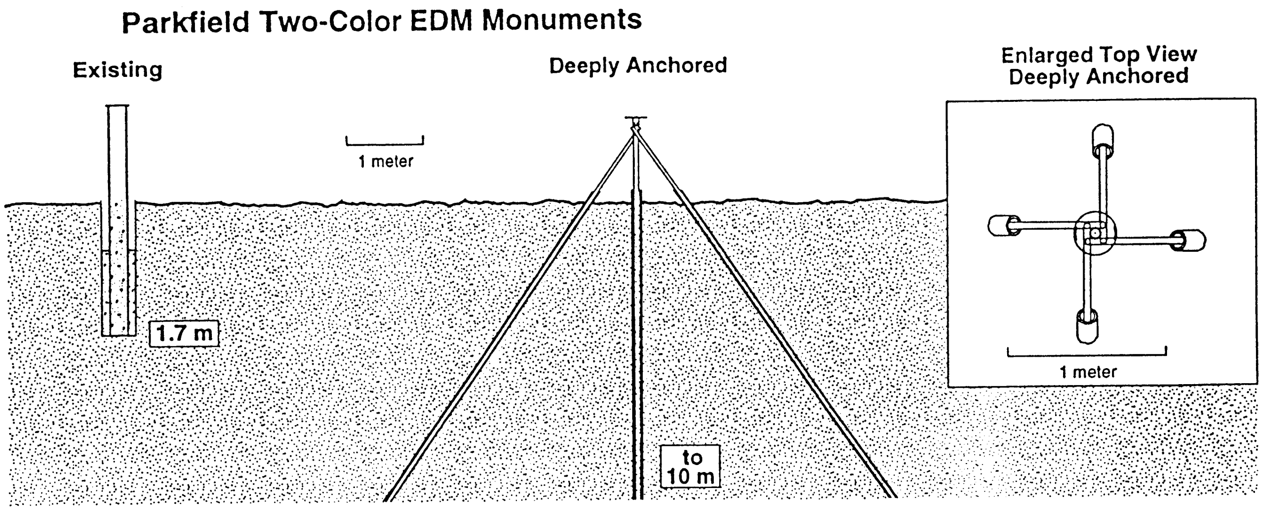
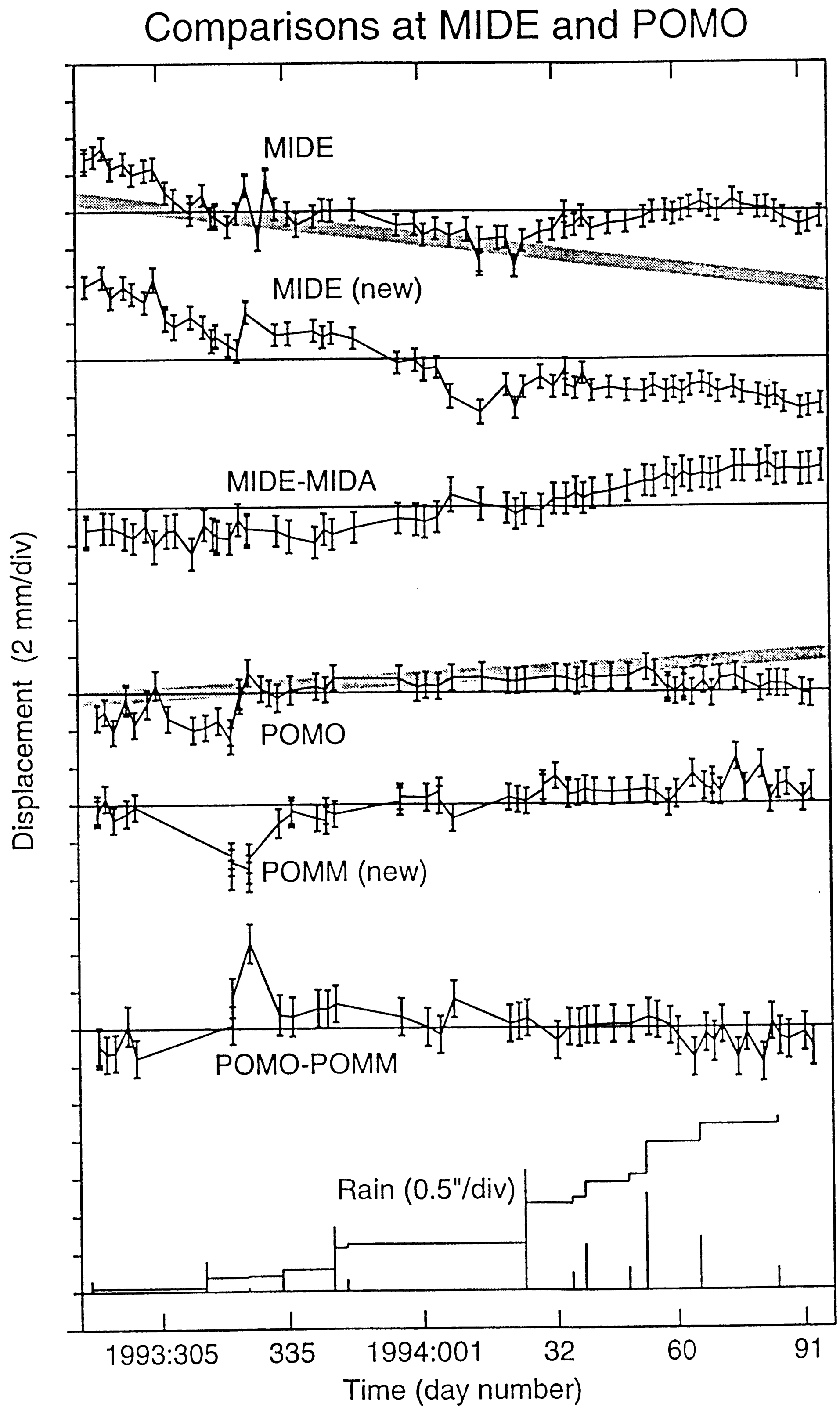


Figure 3-4

of the long-base tiltmeter; the goal at that time was for NGS, and Dr. A. Sylvester (UCSB) to use levelling to establish the vertical stability of these relative to the tiltmeter end-piers, as a supplement to the results of Sylvester (1984). More recently, we have built several designs of stabilized monument nearby, two of them used for the permanent GPS array. We have also colocated stabilized monuments at two other points of the 2-color network operated by the USGS, to improve the stability of the strain estimates it gives—and also to evaluate the stability of the marks. For these monument clusters the survey data comes largely from short-range surveys we perform using a precise EDM (Wild DI2000, error of 0.5 mm), purchased with NASA funds, and also from the 2-color data collected by Dr. Langbein. The second approach was the construction, last summer, of two monuments at Parkfield, again both to help the two-color work and to serve as a test of our techniques.[7] The marks selected, POMO and MIDE, are both known to be unstable and are also particularly important, since they are both on Middle Mountain, directly above the anticipated initiation zone.

Figure 3-5 shows some early results from Parkfield, comparing the 2-color data from the conventional monuments MIDE and POMO (already shown in **Figure 3-2**) with the data from the new marks MIDA and POMM (these were instrumented with retroreflectors, and the data were supplied by, Dr. Langbein); these are within 20 m of the original marks in both cases. For this early part of the test the rainfall at Parkfield, the main driver of monument motion, was at a 9-year low: 17 cm for this season, as opposed to 30-60 cm/yr for the preceding three years. It is noticeable in **Figure 3-2** that MIDE did not show the sharp increase of the last few years. Nonetheless, a 4-mm increase in length is visible starting in January 1994, and this is not seen in the data from the stabilized mark MIDA (refer to MIDE–MIDA, or the shaded band which for both sites suggests the trend of the new marks). There does not appear to be as much difference between the data for POMO and POMM in this plot. Much of this stems from the need to account for the motion of the central site before interpretation of the individual line lengths. The fuller record (Langbein *et al.*, 1996), shows about equal improvement for both sites, and has given considerable insight into the range of behavior possible from the conventional marks.

[7] This was an unexpected project; we had funds with which to do it because of the departure of our graduate student and because of the 5% pay cut for UC employees.



Comparisons at MIDE and POMO
MIDE
MIDE (new)
MIDE-MIDA
POMO
POMM (new)
POMO-POMM
Rain (0.5"/div)
Displacement (2 mm/div)
1993:305
335
1994:001
32
60
91
Time (day number)

Figure 3-5

Table 3.1: Deeply Anchored Marks

Name	Built	Type	Location	Purpose	Comments
PIN1	1989	A	PFO	PGGA	First deep-anchored mark
PIN2	1989	B	PFO	GPS	Auxiliary mark for permanent GPS at PFO
VAND	1991	A	Pt. Conception	PGGA	
PIN3c	1992	C	PFO	2-color	First ground-level mark
GREENc	1992	C	Pinyon Flat	2-color	
PF5c	1992	C	Pinyon Flat	2-color	
SIO3	1993	A	La Jolla	PGGA	Replacement for mark destroyed by new building.
MNPK	1993	B	Monument Pk.	PGGA	
MIDA	1993	B	Parkfield	2-color	
POMM	1993	B	Parkfield	2-color	
CSUN	1995	B	Los Angles	SCIGN	
TABL	1995	B	Los Angles	SCIGN	

Types: A–removable tripod; B–fixed tripod, mark elevated; C–mark at ground level.

Table 3.2: Monument Stability Clusters

	Name	Built	Description
PFO	PIN1	1990	Deeply anchored
	PIN2	1990	Deeply anchored
	PIN3c	1992	Deeply anchored: survey reference point
	PF4	1979	Shallow rod mark
	PIN101	1993	Shallow concrete-base mark
	PIN102	1993	Shallow concrete-base mark
	NGS#1-5	1986	Class-A rod marks (5)
Green	NCER-1982	1982	Shallow concrete-base mark
	Green EC-1	1984	Rod mark
	Greenc	1992	Deeply anchored: survey reference point
PF5	PF No.5-1982	1982	Plinth
	Pinyon 5	1984	Rod Mark
	PF5a	1986	Rod Mark
	PF5c	1992	Deeply anchored: survey reference point
DHL	SVL1-3	1994	Shallow driven rods
	CUBD	1995	Borehole mark
	NVL1-3	1994	Shallow driven rods

Though we began to make precise EDM surveys between some of the monument clusters at PFO late in 1992, a certain amount of effort in the early surveys was spent on gaining experience in conventional survey techniques: getting results good to the nearest millimeter turns out to be not a simple task, but we have now (the summer of 1995) codified the procedures so that we can have part-time undergraduates do them—with much training. We have already gotten some interesting, if somewhat counterintuitive results, which we show in **Figure 3-6**.

PFO Monument Motions

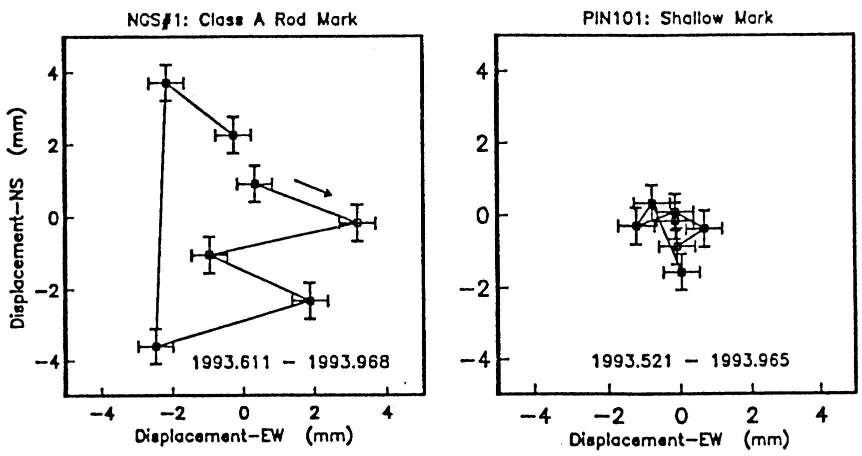


Figure 3-6

These plots show the motion of a mark relative to the reference point PIN3c; the type of mark is described in Table 3-2. The surprise in these data is the stability of PIN101, a shallow mark; but it should be noted that the time covered (several months) does not include this winter's rains. These results indicate that we can indeed track the motion of the mark to within 1 mm, since they are clustered within this range. By contrast, the data for the NGS Class A rod-mark (NGS 1) show large fluctuations (as do the other NGS marks), clearly indicating that this design (developed for vertical stability, though because of the effort involved in construction, considered useful for GPS) is not be as stable in the horizontal as is generally thought: an important conclusion, given that the current NGS GPS network for monitoring crustal motion in California, the HPGN, relies heavily on such marks.

Because of the potential value of these measurements in the long term we are striving to continue the surveys between monuments at PFO to keep track of the stability of different monument types. We have been employing part-time undergraduates to do much of this work, which keeps the cost down, but still demands a significant involvement on our part if good results are to be gotten. We also have, in parallel to this, an effort to make similar measurements at our laser strainmeter site at Durmid Hill. One result of this operation is that we have, in the end-monuments of this instrument, two stable reference points. We have already established some shallow monuments nearby and hope to continue to survey to them (and to an existing section corner) as we now do at PFO, to establish typical monument stability in this quite different (and much less stable) environment. These results will have a bearing on any geodetic studies that may be made in this area, as well as those already done (Sylvester *et al* 1993).

4. Analysis of Crustal Deformation

4.1. Detection of Subseismic Motions

With the planned proliferation of continuous GPS stations, and possibly other sensors, we face the problem of how to process disparate deformation data in order to make inferences about motions that are too slow to excite seismic waves. We have faced this question for the Landers data (Section 2.3), but more general methods are needed, not least to decide how many of what type of sensor to deploy. For example, the data in **Figure 3-1**, converted to strain, show that continuous GPS is inferior, except at periods of a year or more, to the best continuous strain and tilt measurement. However, this does not address the real question, which is: How useful is GPS, and instrumental strain, for detecting sources of subseismic motions? If the GPS receiver that we are using for continuous recording is much closer to the source than the strainmeter, which instrument is better at detecting it? And, how may we combine the data from these two kinds of measurements in order to decide how much motion has occurred, if any?

To give another illustration, this time for a recent source, we show in **Figure 4-1** the strain data at PFO from the Northridge earthquake: both raw, and filtered to remove the coda, leaving very clear coseismic offsets (which, as usual, agree with a dislocation model). The coseismic offsets were also observed at two stations of the PGGA (JPL and PVER); and although these were much closer to the earthquake, the signal/noise ratio for daily estimates (Y. Bock, pers. commun.) is about the same as that seen in the strain in **Figure 4-1**.[8]

In trying to answer some of the questions above, it is useful to begin by posing them more formally, since it is then clear that answering them involves different approaches.

1. First, are the records that we observe anomalous in some way? This involves two issues. (1) It may simply be a matter of statistics, deciding whether the records show a significant departure from previous behavior; and for this we can apply some of the concepts of signal detection theory, as has been done by Langbein *et al.* (1993) for some of the sensors at Parkfield. (2) In practice, deciding that there is an anomaly also involves a certain degree of experience; given that there is a statistically significant departure, it often requires familiarity with the instruments in order to decide whether this departure is due to tectonics, monument motion, or simply adjustments by field personnel.

2. Given a set of data which do *not* appear to show anything anomalous, what limits do such data place on fault motion in one or more places, previously determined by other data? Judging by our experience at PFO, this is an important question; not uncommonly some other phenomenon (such as seismicity or fault creep) shows an interesting variation, and we are asked if we "see anything", and if not what bounds we can set. This is a fairly straightforward problem of statistical inference, though to address it we need to know both the statistics of instrument behavior (as for (1)) and also the response to the source.

3. If we do see an anomaly, what kind of source is it consistent with? This is a much more difficult question because of the many possible sources, as we have seen for the Landers earthquake.

4. Finally, if we plan to install an array of sensors measurements, what in fact will their abilities be in terms of detecting motion on different segments of nearby faults, and isolating the possible source? This is a question that makes use of the same tools as for the other questions; though our concern is with what might be detected rather than what has been for data already in hand.

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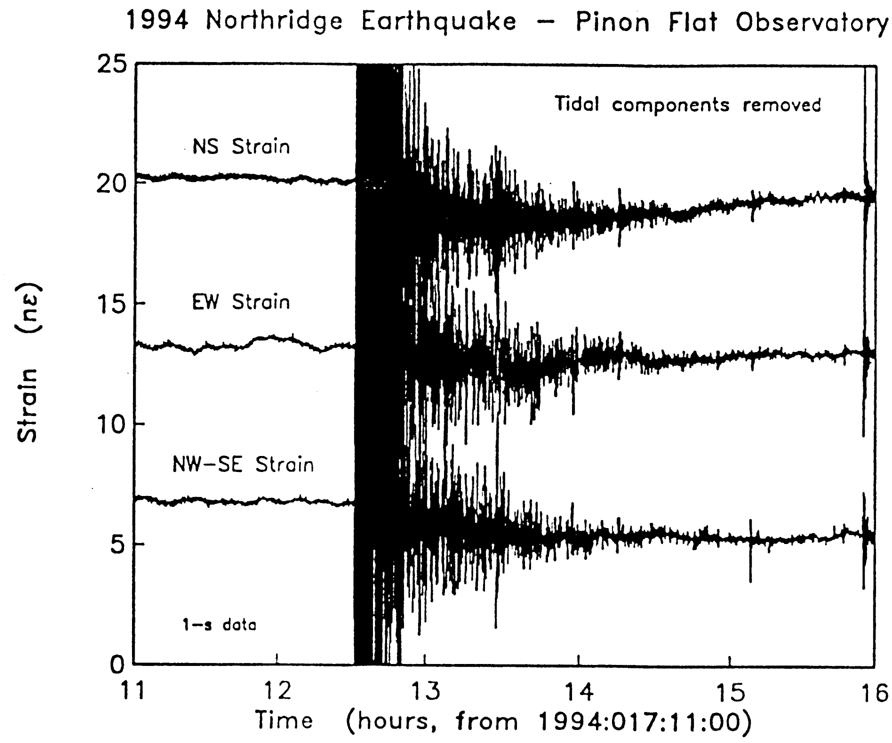
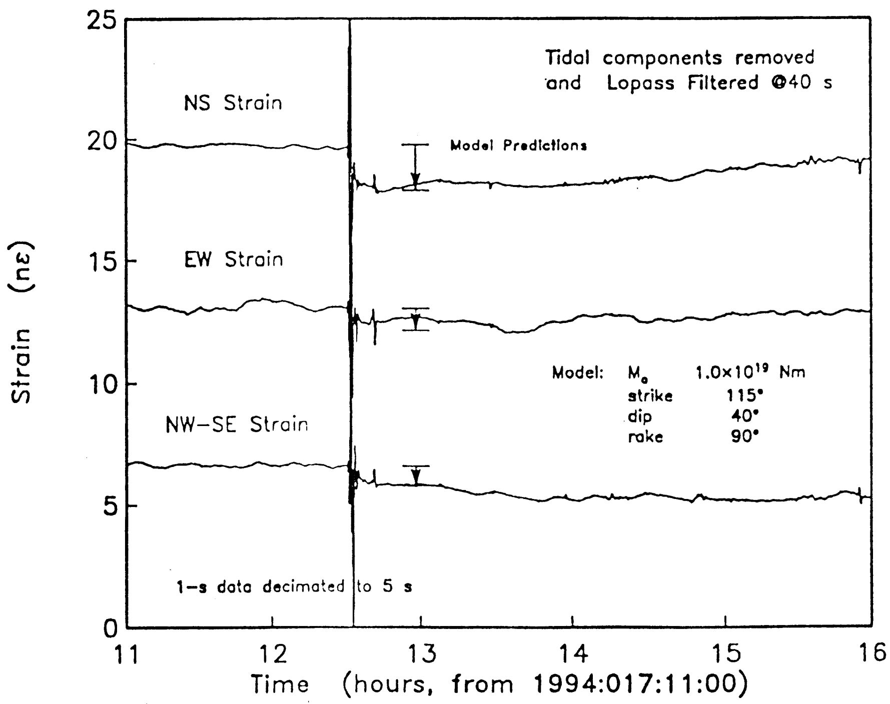
[8] A much less certain signal was seen on the two PGGA stations in the Los Angeles area during late 1993, preceding Northridge, though now largely discounted. The PFO data for this time (**Figure 2-1**) do not show any anomalies; while it would be exciting to argue that the signal at PFO in early 1993, and the PGGA signal later on, are evidence for a propagating strain wave, this is an argument we do not feel is justified.



1994 Northridge Earthquake – Pinon Flat Observatory
Tidal components removed
NS Strain
EW Strain
NW–SE Strain
1–s data
Strain (nε)
25
20
15
10
5
0
11
12
13
14
15
16
Time (hours, from 1994:017:11:00)



Tidal components removed
and Lopass Filtered @40 s
NS Strain
EW Strain
NW–SE Strain
Model Predictions
Model: M0 1.0x10^19 Nm
strike 115°
dip 40°
rake 90°
1–s data decimated to 5 s
Strain (nε)
25
20
15
10
5
0
11
12
13
14
15
16
Time (hours, from 1994:017:11:00)

Figure 4-1

As noted above, for all but question (1) we need to know two things: the connection between the source and the recorded deformation data, and a characterization of the instrument noise. For the first, we use the model of a dislocation in a half space; this has successfully explained most data on coseismic offsets, and also the long-term geodetic data on strain accumulation around faults. For the instrument noise, Agnew (1992) shows how to find the amount of wander expected over a period of time from the power spectrum of past data. For deformation modeling, the wander over some time τ is the quantity of interest, since we are interested in the amount of change from some previous state.

If the expected wander over time τ on instrument k is $n_k(\tau)$, and the signal is s_k, the ratio s_k/n_k is a simple measure of detection. Assume that the signal is given by

$$s_k(\theta_k,\phi_k,\tau) = m(\theta_i,\phi_i,\tau)g_k(\theta_k,\phi_k,\theta_i,\phi_i) = m_i(\tau)g_{ki}$$

Here m is the amount of slip over time τ at a fault located at coordinates (θ_i,ϕ_i) and g_k is the Green's function connecting this slip to the signal s_k recorded at an instrument at another location; the subscript k thus refers to the site location as well as to instrument type.

To discuss the detection capability for a network of sensors, assume that the measure of signal detection is

$$|s_k| > b(\alpha_0)n_k \qquad (1)$$

where α_0 is the probability of a false alarm. To apply this to network detection we ask, for a given fault patch, what the minimum slip is to satisfy (1) for at least one sensor.[9]

Figure 4-2 shows the results of such a computation for two classes of networks, both presently running: in the two left plots for just the laser strainmeters at PFO and DHL (the new site near the Salton Sea), and, in the two right plots, for these and also the permanent GPS stations of the PGGA. The detection level is taken to be 3σ on at least one sensor, and right lateral strike slip has been assumed as the source motion. The noise level n on the strainmeters has been been taken to be 1 nε for τ one day, and 10 nε for τ one month. Based on the "cleaned" position data of Bock and Wdowinski (Y. Bock, pers. commun), we have taken n for continuous GPS to be 2 mm NS and 4 mm EW from day to day; since the errors are roughly white, the wander between two days a month apart (the measure used for the strain data) is the same. The results are plotted in terms of moment magnitude, with symbol size increasing for smaller magnitudes, and going to zero for equivalent moment magnitude 6.5, which would be a very large subseismic event.

The result shows that at periods of a day (top plots) the existence of continuous GPS does not change the detection levels already set by the strainmeters, simply because the strainmeters are so low-noise at these periods. For the faults close to the strainmeters the level is equivalent magnitude 4–4.5. For events evolving over monthly periods (bottom two plots) the increased noise of the strainmeters means that the detection threshold is not as good: for those segments far from the strainmeters the threshold becomes high enough that the limit is instead set by the (closer) PGGA stations—though the threshold from them is rather high, requiring something to occur with equivalent magnitude 6.

[9] A more conservative approach would be to adopting the detection algorithm outlined by Beroza and Jordan (1990) for detection of silent earthquakes from free oscillation data; this requires some larger number of sensors to show a signal. Unfortunately it works poorly for this case because the expected amplitude can be very different on different sensors, just depending on location.

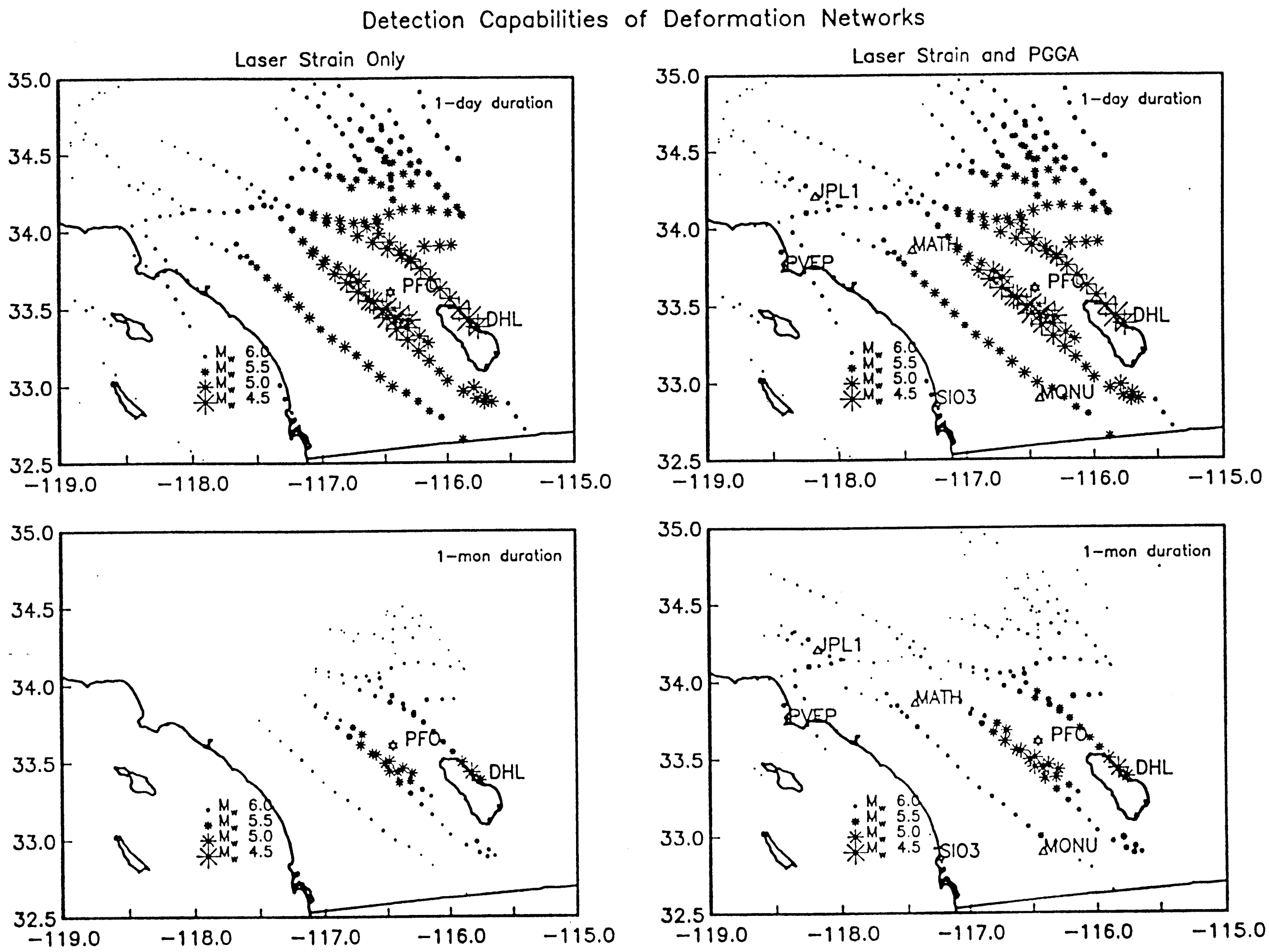


Figure 4-2

The results in **Figure 4-2** are preliminary, and need to be refined by including more realistic estimates of the noise level; this will be necessary before we try to make deployment decisions based on such maps. As Section 3.1 indicates, we would hope to be developing these for short-range GPS from the data we have been collecting; we also would like to work with Dr. Bock to examine the PGGA data in just these terms. We would expect this collaboration to be very fruitful.

This simple approach to signal detection begs the question of how to choose τ in the first place, and also makes less use of the statistics of the data than would be desirable. Fuller use of the theory of signal detection (Langbein *et al.*, 1993; Helstrom 1968) should allow us to design a better way of monitoring for anomalous behavior, both in single instruments and in networks. As noted above, the different sizes of signal expected in different locations also complicates the problem: we would like to demand multiple detections, but if we saw a very large signal at one instrument, we would at the very least be seriously concerned. How to formulate this more precisely so that we may answer the question of how best to design deformation-monitoring networks is something we would like to work on under future support. We would also seek to develop methods that would make use of the physics of the problem, not just pure statistics: to produce a method that will correctly respond to actual signals, but reject as inconsistent any signals that could not have been produced by the earth. A number of possible approaches have been developed by the signal detection community for this problem of evaluating multiple hypotheses, and we would like to build on these existing techniques. Of course, once the algorithms were devised we would be in a very good position to test them on real-time data from PFO and the PGGA, since the proof of the efficacy is in their response to real-world situations.

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